METEORITE SCARS IN ANCIENT ROCKS

John D. Boon and Claude C. Albritton, Jr.

In a previous paper[1] the writers suggested that some explosion structures currently attributed to volcanism may actually record impacts of giant meteorites which fell during the geological past. It is the purpose of this article to show how meteorite craters and their underlying structures might be preserved, and to evaluate the meteoritic hypothesis as an explanation for three structures which tentatively have been assigned to other origins.

Geological Results of Meteorite Impacts

It is doubtful whether the meteoritic origin of the great Arizona crater, and like features in other parts of the world,[2] would ever have been conceded had there not been associated silica glass and meteorite fragments. Yet these most convincing clues are just the ones which will disappear first under the onslaught of weathering and erosion. In time the craters themselves will become filled with sediment or breached by headward-eroding streams, and so will lose their characteristic forms. Since the recognized meteorite craters are very youthful features, geologically considered, additional criteria will be needed for recognition of meteorite scars in ancient rocks. Two methods of attack are suggested. In the first place, we may ascertain the geological features known to have been produced by meteorite impacts. Secondly, we may appeal to a theoretical consideration of effects produced by a projectile comparable to a large meteorite[3] striking a medium such as the earth's crust.

---

[1]Boon, J. D., and Albritton, C. C., Jr., "Meteorite Craters and Their Possible Relationship to 'Cryptovolcanic Structures'," *Field and Laboratory,* Vol. 5 (1936), pp. 1-9. This paper should be read in connection with the present article.

[2]Spencer, L. J., "Meteorite Craters as Topographical Features on the Earth's Surface", *Smithsonian Inst. Ann. Rpt.,* 1933, pp. 307-325, 5 pls.

[3]By a "large" meteorite the writers mean one 100 or more feet in diameter. See Boon, J. D., and Albritton, C. C., Jr., op. cit., footnote 3, p. 3.

The best known meteorite locality, that near Flagstaff, Arizona, shows the following characteristics which may be considered generic. [4 5 6 7]

1. An almost circular explosion crater with silica glass and meteorite fragments scattered around it.

2. A rim of ejected material ranging in size from rock flour to large boulders.

3. Extreme brecciation, pulverization, and local fusion of the country rock along the sides of the crater.

4. Radially outward dip of strata exposed along the crater walls. (This strongly suggests that beds beneath Meteor Crater are domed. Whether there are ring folds around a central dome, as would be expected in an explosion structure, is not certain.)

5. A remarkable bilateral symmetry in distribution of faults, degree of radial dip of beds, and location of large boulders in the rim (Fig. 1). This would seem to indicate that whereas the crater is roughly circular in plan, the underlying structure is bilaterally rather than radially symmetrical.

It is difficult to comprehend the tremendous pressures which would be produced in the brief interval between impact and explosion of a large meteorite. The writers have previously shown that under certain reasonable conditions respecting size and velocity of projectile, these pressures may reach the enormous values of fifteen million atmospheres.[8] Moulton, by using somewhat different assumptions, obtains a value more than twice as great.[9] In the discussions that follow, these unprecedented pressures should be kept in mind, for they bring about the terrific explosions, the excavation of the craters, and the backfiring and shattering of the meteorites.[10]

---

[4]Barringer, D. M., "Coon Mountain and Its Crater", *Acad. Natural Sciences of Philadelphia Proc.*, Vol. 57 (1906), pp. 861-866.

[5]Tilghman, B. C., "Coon Butte, Arizona", 1. c., pp. 887-914.

[6]Barringer, D. M., "Further Notes on Meteor Crater, Arizona", 1. c., vol. 66, (1915), pp. 556-565.

[7]Rogers, A. F., "A Unique Occurrence of Lechatelierite or Silica Glass", *American Jour. Science* (5), Vol. 19 (1930), pp. 195-202.

[8]Boon, J. D. and Albritton, C. C., Jr., op cit. p. 5.

[9]Moulton, F. R., *Astronomy*, Macmillan Co. (1931), p. 305.

[10]For evidences of explosions produced by impact of meteorites see: Boon, J. D. and Albritton, C. C., Jr., op. cit., p. 6.

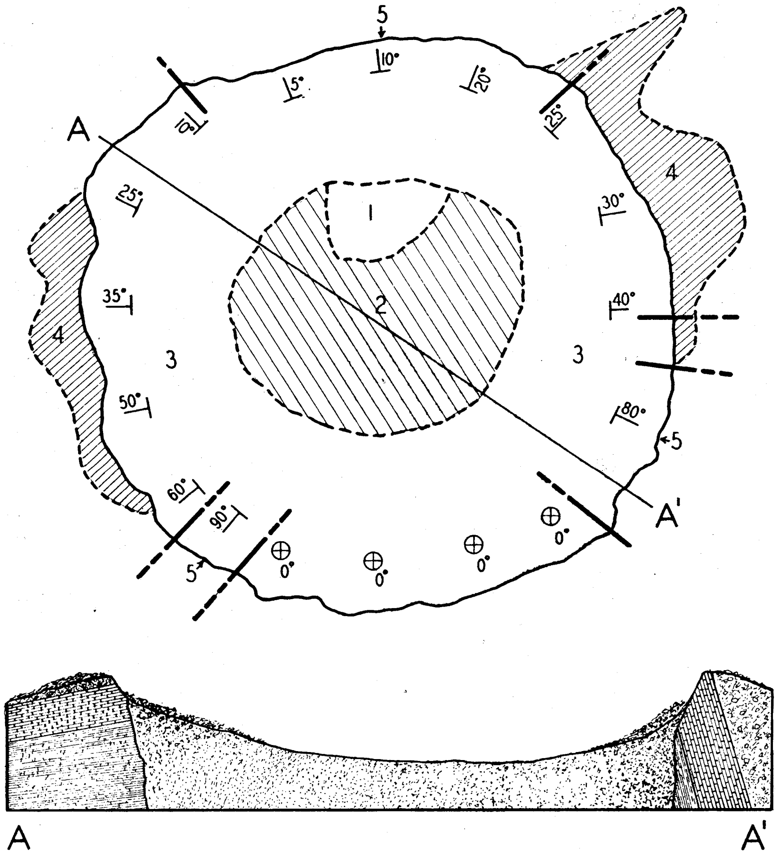

Fig. 1. Map and section through Meteor Crater, Arizona, simplified and slightly modified from Barringer (*Proc. Acad. Nat. Sci. Phila.* 1914, Pl. XXI). 1. Silica Hill. 2. Floor of crater formed on lake deposits. 3. Inner slopes of crater. 4. Areas in which large boulders are concentrated in rim. 5. Margin of rim. Section shows unsymmetrical tilting of strata on opposite sides of crater.

"When a large meteorite strikes the earth, it deals a terrific blow to a medium which has a limited degree of freedom and a high degree of elasticity of volume. It should be remembered that while some of the materials, such as clay, composing the crust of the earth, have little or no elasticity of shape, they all have great elasticity of volume. Brittle substances are not shattered by pressure, if the pressure be applied to all sides, but by tension. Hence after compression they all rebound.

"Therefore, as a result of impact and explosion, a series of concentric waves would go out in all directions, forming ring anticlines and synclines. These waves would be strongly damped by the overburden and by friction along joint, bedding, and fault planes. The central zone, completely damped by tension fractures produced in rebound, would become fixed as a structural dome.

"The general and simplest type of structure to be expected beneath a large meteorite crater would, therefore, be a central dome surrounded by a ring syncline and possibly other ring folds, the whole resembling a group of damped waves."[11] The writers' concept of an ideal section through a meteoritic structure is shown in Fig. 2.

Aspects and Preservation of Meteorite Scars

Evidently the bolide which produced Meteor Crater formed also a faulted, domical structure which is likely to persist as a "meteorite scar" long after the crater, ejectamenta, and meteorite fragments have been removed by weathering and erosion.

The aspect of a meteorite scar will depend primarily on the level to which the area has been denuded subsequent to impact. This is made clear by referring to Fig. 2. It is only in the initial stage (along the profile AA) that the crater clearly reflects its origin in the rim of ejected material, silica glass, and meteorite fragments distributed about it. The scar will become inconspicuous when the country is denuded to the level BB. When the area is down to the level CC the underlying structures begin to appear, and when the depth DD is reached the central uplift and ring folds become apparent. Should erosion proceed to depths below those affected by the meteoritic disturbance, the scar would be obliterated. On the other hand if the scar should be submerged and covered with sediments, it might be preserved and subsequently revealed in the course of regional uplift and erosion.

Possible Examples of Meteorite Scars

Previously the writers pointed out the striking similarity

---

[11] *Ibid*, pp. 6, 7.

between certain American "cryptovolcanic structures" and those which would be produced by impacts of giant meteorites.[12] [13] The cryptovolcanic and meteoritic hypotheses are

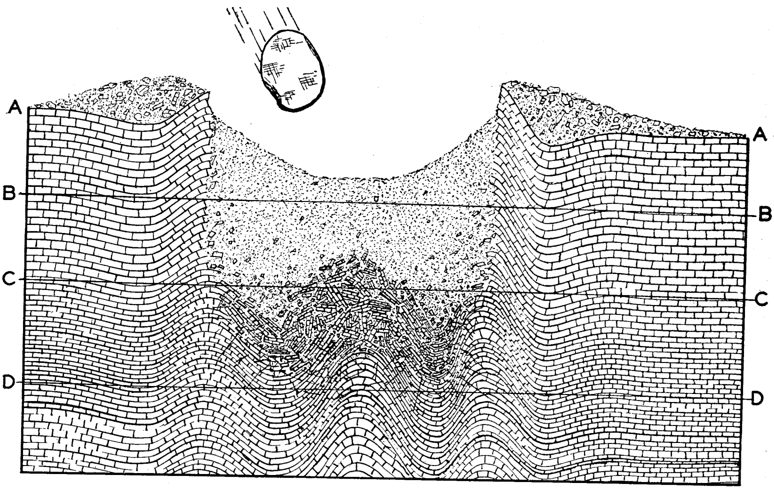

Fig. 2. Ideal section through a meteorite crater according to the writers' concept of structures produced by impact and explosion. (For explanation of lettered lines see text.) Relative size of a meteorite believed to be capable of forming the scar shown is indicated above the crater.

strikingly similar in that each supposes tremendous explosions to have entered into the formation of the structures in question. In the one case the explosions are believed to have resulted from sudden release of subterranean gases, in the other the explosions are believed to have followed impacts of massive, swiftly-moving projectiles.[14] Either hypothesis is adequate to explain the presence of intensely disturbed, subcircular structures with central domical uplifts surrounded by ring folds resembling damped waves. Either hypothesis can account for evidences of violent, explosive forces manifest in brecciation and minor faulting. It appears, however, that the meteoritic hypothesis can account for two features which are unsatisfactorily explained by

---

[12]Boon, J. D., and Albritton, C. C., Jr., op. cit. pp. 7-9.

[13]Bucher, W. H., "Cryptovolcanic Structures in the United States", *Rpt. XVI International Geological Congress* (1936), Vol. 2, pp. 1055-1084.

[14]Boon, J. D., and Albritton, C. C., Jr., op. cit. pp. 3-6.

the alternate mechanism. These are (1) the distinctly bilateral structural symmetry found in several American examples, such as Wells Creek, Jeptha Knob, and Serpent Mound, and (2) the absence of volcanic materials and signs of thermal activity.[15] It is more difficult to explain how an upwardly directed explosion alone could produce a bilaterally symmetrical structure (sometimes with overturning of beds in one quadrant only) than it is to see how an obliquely impinging meteorite could produce a radially symmetrical structure.[16] However, as the angle of incidence of an impinging meteorite approaches zero, the resulting scar should approach radial symmetry, so that the meteoritic hypothesis must be considered in explanation of both radially and bilaterally symmetrical explosion structures.

Flynn Creek Structure

Flynn Creek disturbance, near Gainesboro, Tennessee, marks the site of a great explosion which occurred in early Kinderhook or late Devonian time.[17] The resulting subcircular crater, two miles across and over 300 feet deep, was partly filled with lake deposits and the surrounding region eroded before it was covered over by the sediments of the Chattanooga sea. Ordovician limestones around the walls of this ancient crater dip radially away from the center on the north, east, and west sides, but on the south side they have been thrust away from the center and overturned.[18] No volcanic materials are associated with the disturbance.

Wilson and Born believe that this structure is cryptovolcanic. They dismissed the possibility that the disturbance was formed by impact and explosion of a meteorite because they believed it would not explain "the central uplift of 500 feet . . . that raised Lowville limestone up to the level of the Leipers formation." It seems this argument overlooks the fact that elasticity of rocks would cause a strong rebound following intense compression pro-

---

[15]Bucher, W. H., op. cit., p. 1074.

[16]Boon, J. D., and Albritton, C. C., Jr., op. cit. pp. 6,7.

[17]Wilson, C. W., and Born, K. E., "The Flynn Creek Disturbance, Jackson County, Tennessee", *Journal of Geology*, Vol. XLIV (1936), pp. 815-835.

[18]*Ibid*, p. 826.

duced by impact and explosion. It is not unreasonable to suppose that the height of this rebound would be directly proportional to the diameter of the crater, with a ratio as shown in the ideal section, of about one to ten. A rebound of this amplitude would be quantitatively adequate to explain the elevation of the rock in Flynn Creek and other structures.

It appears, therefore, that the meteoritic hypothesis, as well as the cryptovolcanic, is able to account for the salient features of the Flynn Creek disturbance: the ancient explosion crater, the extreme brecciation and pulverization of materials in the center, and the considerable upward displacement of breccia blocks.

The bilateral structural symmetry, with overturning of beds on the south side, appears to be a cogent argument in favor of the meteoritic hypothesis, for it is difficult to imagine an upwardly-directed gas explosion causing overturning on one side of the crater only. Again the dip of beds around Meteor Crater provides a striking analogy (Fig. 1). These dips increase more or less symmetrically from 5 to 10 degrees on the northern extremity around both east and west sides, to 80 and 90 degrees on the south. Barringer shows an extreme southerly octant bounded by tear faults and underlain by horizontal strata. One wonders if the beds in the southerly octant are not overturned, especially in view of the fact that vertical, or near-vertical, beds adjoin this segment on both sides; and in consideration of the following somewhat enigmatic statement of Tilghman.[19]

> These strata themselves dip downward and outward from the center of the hole at an angle of, on the average, about thirty degrees, although this varies in places from more than vertical or inclining backward to about ten degrees.

A magnetometer survey of the Flynn Creek area showed a well-developed magnetic high centered about four miles south-southwest of the structure in question.[20] Wilson and

---

[19]Tilghman, B. C., op. cit. p. 893. (Tilghman does not state whether the strata that are "inclined backward" occur at the southern end of the crater.)

[20]Wilson, C. W., and Born, K. E., op. cit., p. 830, fig. 8.

Born believe this indicates a buried plug of igneous material responsible for the explosion. Granting this magnetic high reflects the presence of a plug, one wonders if the offset of four miles from the center of the disturbance is adequately explained by the "high-angle dip to the north of magnetic lines of force in the earth's surface." Taking the magnetic dip at this point as 68° and solving for the depth of the plug, an answer of about ten miles is obtained. ($90°-68°=22°$; $\tan 22°=4/X$. $X=10$ miles.) It is difficult to see how a relatively small plug at this depth could greatly effect the magnetic field at the surface. Granting that the plug is approximately beneath the structure, it is not evident why the shattering of the roof above the intrusion did not allow ejection of igneous materials. Again, it is well to remember that magnetic anomalies are not uncommon in this part of the United States as any good magnetic map will show: hence the above association may be accidental.

With the exception of the anomalous magnetic high to the south of the structure, the meteoritic hypothesis seems adequate to account for the Flynn Creek disturbance.

Sierra Madera

The Flynn Creek disturbance is suggestive of a meteorite scar which retains evidence of the original crater. By way of contrast, Sierra Madera dome, 25 miles south of Fort Stockton, Texas, suggests a scar from which the crater and its filling have been completely removed by erosion, so that the underlying structures are revealed.

According to King[21] the uplift is roughly circular in plan and about three miles in diameter (Fig. 3). Abruptly updomed Permian strata stand nearly vertically, or dip radially outward at high angles. On the south side overturned beds incline toward the center of the dome at angles of 60 to 70 degrees. Hard dolomitic limestones in the center are unmetamorphosed, but are highly fractured, jointed, and apparently "jumbled and twisted in hopeless disorder."[22]

---

[21]King, P. B., "The Geology of the Glass Mountains, Texas, Part I, Descriptive Geology", *University of Texas Bull. 3038,* (1930), pp. 123-125.

[22]*Ibid,* p. 123.

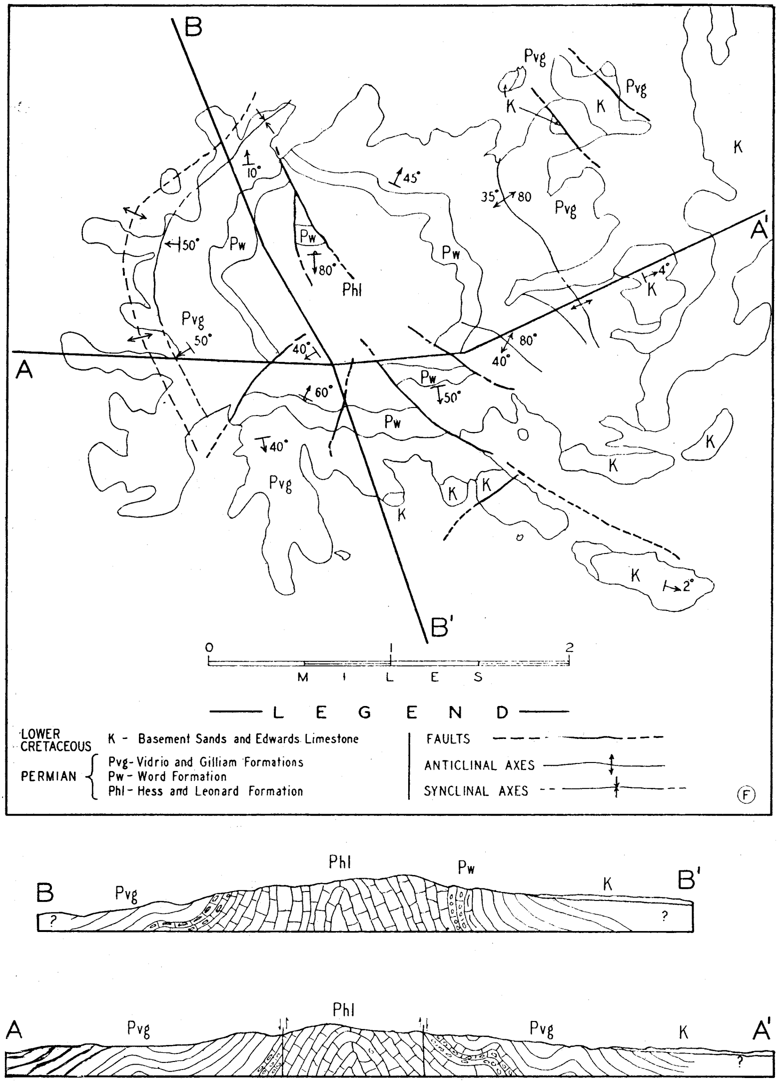

Fig. 3. Map and structure sections of Sierra Madera, Texas, simplified from P. B. King (*Univ. Texas Bull.* 3038, 1930, fig. 42, p. 123).

Radial tear-faults displace the rocks in the center, and small folds flank the uplift to the east and west. On the eastern flank Cretaceous rocks rest unconformably on the Permian, thereby dating the intense deformation as post-Permian and pre-Comanchean.[23]

The following features can be explained by the meteoritic hypothesis.

1. The abrupt central uplift.
2. The fracturing and jointing of rocks in the center.
3. The radial tear-faults.
4. Flanking, arcuate folds resembling damped waves.
5. Bilaterally symmetrical pattern of faults and folds about a line trending north-northwest.
6. Absence of volcanic materials.

Vredefort Dome

King[24] has compared Sierra Madera uplift with the Vredefort dome in the northern part of the Orange Free State. The African structure[25] is an almost circular uplift 75 miles in diameter, with a core of non-intrusive granite 25 miles across, which makes it comparable in size with the larger craters on the moon. Younger rocks girdling the core are in many places overturned so as to dip toward the center of the dome; elsewhere they dip radially outward at high angles. Hall and Molengraaff have emphasized that any explanation of the geological history of the area must first of all account for the following features:

> 1. An almost truly circular area of relatively passive non-intrusive Vredefort Granite, surrounded by
>
> 2. A girdle of highly inclined and often overtilted younger sediments extending from the base of the Witwatersrand System upwards through not less than 10,000 m. of thickness, and frequently seen dipping into the central granite.
>
> 3. Within this girdle a strongly marked polymetamorphism, of which one phase carries its effects concentrically all round the granite, while the other distributes its results excentrically to that formation.[26]

---

[23]King has interpreted the fact that Cretaceous beds dip radially away from the dome at low angles from 2 to 10 degrees as indicative of a second, post-Comanchean, period of uplift. Whatever the nature of this later uplift, it would appear to be quite different in origin from the earlier one.

[24]King, P. B., op. cit. p. 125.

[25]Hall, A. L., and Molengraaff, G. A. F., "The Vredefort Mountain Land in the Southern Transvaal and the Northern Orange Free State", *Shaler Memorial Series, Verhandelingen der Koninklijke Akademie van Wetenschappen te Amsterdam* (Tweede Sectie), Deel XXIV, No. 3, Amsterdam, 1925.

[26]*Ibid*, p. 157.

Impact and explosion of a gigantic meteorite could account for the salient structural features of the Vredefort area: a great circular dome with a core of non-intrusive granite surrounded by a girdle of tilted and overturned strata.

It is possible that the striking metamorphic effects found in the rocks that surround the granite dome were largely produced before the time of intense deformation. This metamorphism has been shown to represent in part the combined effects of regional and local elements. The former, due to load, accounts for the metamorphism of the older rocks encircling and resting upon the granite core. Local thermal metamorphism is believed to be due to an intrusion still largely concealed. Offshoots of this intrusion appear as stock-like granite laccoliths. Since these small, essentially concordant intrusives are involved in the doming along with sediments which inclose them,[27] and since they, like the other rocks of the area, are traversed by veins of flinty crush-rock produced at the climax of updoming,[28] it seems reasonable to conclude that the local as well as the regional metamorphism was accomplished before the formation of the Vredefort dome. Thus the polymetamorphism must not necessarily be explained in terms of the forces which brought about the doming.

In the Vredefort memoir it is suggested that the updoming was "initiated by centripetal pressure. The relief of load resulting from this movement caused a younger magma below the granite to become active and to rise and thus to assist the updoming and the upward movement of the much heated but passive granite."[29] Hall and Molengraaff proposed no motivating cause for the development of the centripital pressure,[30] and emphasized the difficulty of accounting for an almost circular dome by appealing to tangential stresses.[31]

---

[27]*Ibid*, p. 65, fig. 3.

[28]*Ibid*, Geological sketch map at back.

[29]*Ibid*, p. 177.

[30]*Ibid*, p. 163, footnote.

[31]*Ibid*, pp. 155-156.

In addition to the features noted previously, the meteorite hypothesis could account for the following:

(1) The transverse and oblique faults around the margins of the core. King[32] has noted the similarity in the fault patterns of the Vredefort and Sierra Madera domes.

(2) The absence of volcanic materials.[33]

(3) The evidences for the operation of unprecedented pressures in association with updoming.

All rocks of the district including the Vredefort granite reveal microscopically the effects of powerful pressure by their being crushed in many places and locally mylonitized.[34] Striking evidence for the operation of great pressure appears in veins of flinty crush-rock which literally riddle the granite and adjoining rocks. Large dikes of enstatite-granophyre may represent extreme developments of crush-rock veins.[35] The great volume of shattered materials estimated to be as high as 800,000,000 cubic meters,[36] sets the Vredefort area sharply apart from superficially similar structures such as the Black Hills dome. Could anything other than a violent explosion have produced this vast amount of crushed rock? Shand has suggested that the flinty crush-rock was formed as a result of shock caused by a "gigantic impulse or series of impulses".[37] Is it possible that this impulse was the impact and resulting explosion of a gigantic meteorite which struck this area in pre-Carboniferous time?

---

[32]King, P. B., op. cit. p. 125.

[33]Hall, A. L., and Molengraaff, G. A. F., op. cit. p. 170.

[34]*Ibid,* p. 51.

[35]*Ibid,* p. 111.

[36]*Ibid,* p. 113.

[37]Shand, S. J., "The Psuedotrachylyte of Parijs", *Quart. Jour., Geol. Soc.* Vol. LXXII (1916), p. 219.